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Abstract

The Social Carbon Cost (SCC) represents the economic damage caused by an additional ton of carbon emissions and is widely used by governments to price carbon. Because the SCC is defined by social welfare, its estimation is necessarily dependent on future assumptions that are difficult to project. Many approaches consider the impact of population or economic growth on the SCC, but these socioeconomic factors must be grounded on solid assumptions concerning political, technological and environmental developments. Over the past seven years, the climate change research community has established five plausible socioeconomic narratives, called ‘Shared Socioeconomic Pathways’ (SSPs), numbered SSP1–SSP5. These scenarios provide descriptions of how the future might unfold in several key areas. To this end, we use the China Climate Change integrated assessment model (C3IAM) and the Dynamic integrated model of Climate and the Economy (DICE) to update the SCC under the five socioeconomic pathways, while also considering alternative damage functions and the social welfare discount rate to address uncertainty. The results show that, in a world developing towards regional rivalry (SSP3), the average SCC today will likely double compared with other scenarios. If additional developing countries emerge that follow the same path as previous industrializations (SSP5), the SCC will experience a rapid increase after 2060. Inequality (SSP4) will experience low mitigation pressure under a sustainable development scenario (SSP1), while the historical development pattern (SSP2) will have a moderate SCC with higher uncertainty. The results can provide carbon price benchmarks for policy makers who hold different attitudes towards the future and can help address the need to avoid regional rivalries and fossil-fueled development, which may counteract mitigation efforts.

Keywords	Climate Change; Integrated Assessment; Social cost of Carbon; Shared Socioeconomic Pathways; C3IAM; DICE

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Dear Editors,

I would like to submit this paper entitled of 'Social Cost of Carbon under Shared Socioeconomic Pathways' for your consideration of potential publication in Global Environmental Change – Human and Policy Dimensions.

The Social Carbon Cost (SCC) represents the economic damage caused by an additional ton of carbon emissions and is widely used by governments to price carbon. Over the past seven years, the climate change research community has established five plausible socioeconomic narratives, called 'Shared Socioeconomic Pathways' (SSPs), numbered SSP1–SSP5. We use the China Climate Change integrated assessment model (C3IAM) and the Dynamic integrated model of Climate and the Economy (DICE) to update the SCC under the five socioeconomic pathways, while also considering alternative damage functions and the social welfare discount rate to address uncertainty.

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We confirm that there are not conflicts of interest for this work.

Sincerely yours,

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Highlights

- We update the social carbon cost under five shared socioeconomic pathways.
- This is the first article to address the socioeconomic impact of social carbon cost.
- The development of regional rivalries will double the present social carbon cost.
- After 2060, social carbon costs will rise to unbearable levels with continued fossil-fueled development.

Social Cost of Carbon under Shared Socioeconomic Pathways

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Social Cost of Carbon under Shared Socioeconomic Pathways

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The Social Carbon Cost (SCC) represents the economic damage caused by an additional ton of carbon emissions and is widely used by governments to price carbon. Because the SCC is defined by social welfare, its estimation is necessarily dependent on future assumptions that are difficult to project. Many approaches consider the impact of population or economic growth on the SCC, but these socioeconomic factors must be grounded on solid assumptions concerning political, technological and environmental developments. Over the past seven years, the climate change research community has established five plausible socioeconomic narratives, called 'Shared Socioeconomic Pathways' (SSPs), numbered SSP1–SSP5. These scenarios provide descriptions of how the future might unfold in several key areas. To this end, we use the China Climate Change integrated assessment model (C^3IAM) and the Dynamic integrated model of Climate and the Economy (DICE) to update the SCC under the five socioeconomic pathways, while also considering alternative damage functions and the social welfare discount rate to address uncertainty. The results show that, in a world developing towards regional rivalry (SSP3), the average SCC today will likely double compared with other scenarios. If additional developing countries emerge that follow the same path as previous industrializations (SSP5), the SCC will experience a rapid increase after 2060. Inequality (SSP4) will experience low mitigation pressure under a sustainable development scenario (SSP1), while the historical development pattern (SSP2) will have a moderate SCC with higher uncertainty. The results can provide carbon price benchmarks for policy makers who hold different attitudes towards the future and can help address the need to avoid regional rivalries and fossil-fueled development, which may counteract mitigation efforts.

Keywords: Climate Change; Integrated Assessment; Social cost of Carbon; Shared Socioeconomic Pathways; C^3IAM; DICE

1. *Introduction*

After the Paris Agreement, countries have increasingly taken actions to address climate change. However, the policy costs vary among countries and sectors, making it difficult to select the most worthwhile policies. This problem can be addressed by calculating the social cost of carbon (SCC), which balances the social costs resulting from emission reductions with the incremental costs of regulation policy. The US government has relied on the SCC estimates provided by the Interagency Working Group (IWG) as a basis for taxing and implementing regulation policies (Revesz et al., 2017). The IWG SCC estimates started in 2010 and were updated with new scientific developments in 2013 and 2016, resulting in policy benefits of more than $1 trillion (Nordhaus, 2017). The SCC is also increasingly being adopted for regulations at the state level, resulting in regulatory policies in California, New York and Minnesota (California, 2016; Larson, 2016; Minnesota, 2016).

Given the wide range of social and climate interactions included in the calculation, SCC estimation is necessarily complex and highly uncertain (Pindyck, 2013). Damage functions and social welfare discounts are considered the two major contributors to this uncertainty (Cai et al., 2016; Diaz and Moore, 2017; Heal and Millner, 2014; Howarth et al., 2014; Pycroft et al., 2014); however, any discussion of these issues is necessarily based on the underlying socioeconomic assumptions. Economic development can alter emission flow patterns (Mi et al., 2017), and—because the SCC is defined by social welfare—population and economic projections are fundamental determinants in its estimation. Scovronick et al. (2017) investigated the influence of future population growth on the SCC, Dietz and Stern (2015) and Moore and Diaz (2015) considered the impacts of climate on economic growth as the drivers of uncertainty. However, the democratic and economic assumptions are only two aspects of the socioeconomic assumption, which may be associated with a wide range of political, technological and environmental contingencies. If the recently imposed steel tariff continues developing and becomes a regional rivalry, it may well alter the historical development path of economic and policy characters, resulting in different SSC patterns.

The SSP framework was initially proposed by Moss et al. (2010) and Van Vuuren et al. (2012), but the quantified and qualified version was published seven years later by Riahi et al. (2017). The five SSPs characterize societal futures that present unique combinations of challenges to carbon mitigation and adaptation, including six broad projected categories, namely, demographics, economy and lifestyles, human development, policies, technology and natural resources. The SSP framework greatly facilitates integrated analyses of mitigation and adaptation. Pizer et al. (2014) revealed the importance of considering the new SSP framework into SCC estimates.

Our paper estimates the SCC under the five SSP scenarios; we also extend our research by considering the uncertainty caused by damage functions and the social welfare discount rate. The results demonstrate the need to avoid regional rivalries and fossil-fueled development, which can raise the current SCC cost or induce much heavier mitigation pressures by the end of this century. The SCC value provides a carbon price benchmark for policy makers who hold different attitudes towards the future and is an important reference for future research under the various SSPs.

2. *Methodology*

2.1 Overview of the methodology

We use the C^3IAM model to characterize the SSP and the DICE model to calculate the SCC. The DICE model is one of the three models used by the U.S. government and has been widely used for SCC estimation by scholars (e.g., (Crost and Traeger, 2014; Moore and Diaz, 2015; Scovronick et al., 2017)). Four variables, namely, the population, gross output, carbon intensity, and adaptation functions may change under different SSPs. However, many serve as exogenous variables in the model, which requires a model that includes detailed descriptions of socioeconomic factors to update these factors. The C^3IAM, developed by Center for Energy & Environmental Policy Research, Beijing Institute of Technology, is an integrated assessment model that is theoretically based on the Computable General Equilibrium (CGE) and long term growth theory (the theoretical basis and structure of C^3IAM are described in the Supporting Information). The C^3IAM model can estimate policy costs under different socioeconomic assumptions and provide an aggregate emissions cost from all sectors. We use the C^3IAM result to update the adaptation function and carbon intensity in the DICE model to embody the differences between SSPs, as described in Section 2.2. Because the SCC is also sensitive to alternative damage functions and to social welfare discounts, we extend our research by considering the uncertainty that arises from these two aspects. The damage functions and alternative social welfare discounts selected in this study are discussed in Section 2.3. An outline of our research is shown in Figure 1.

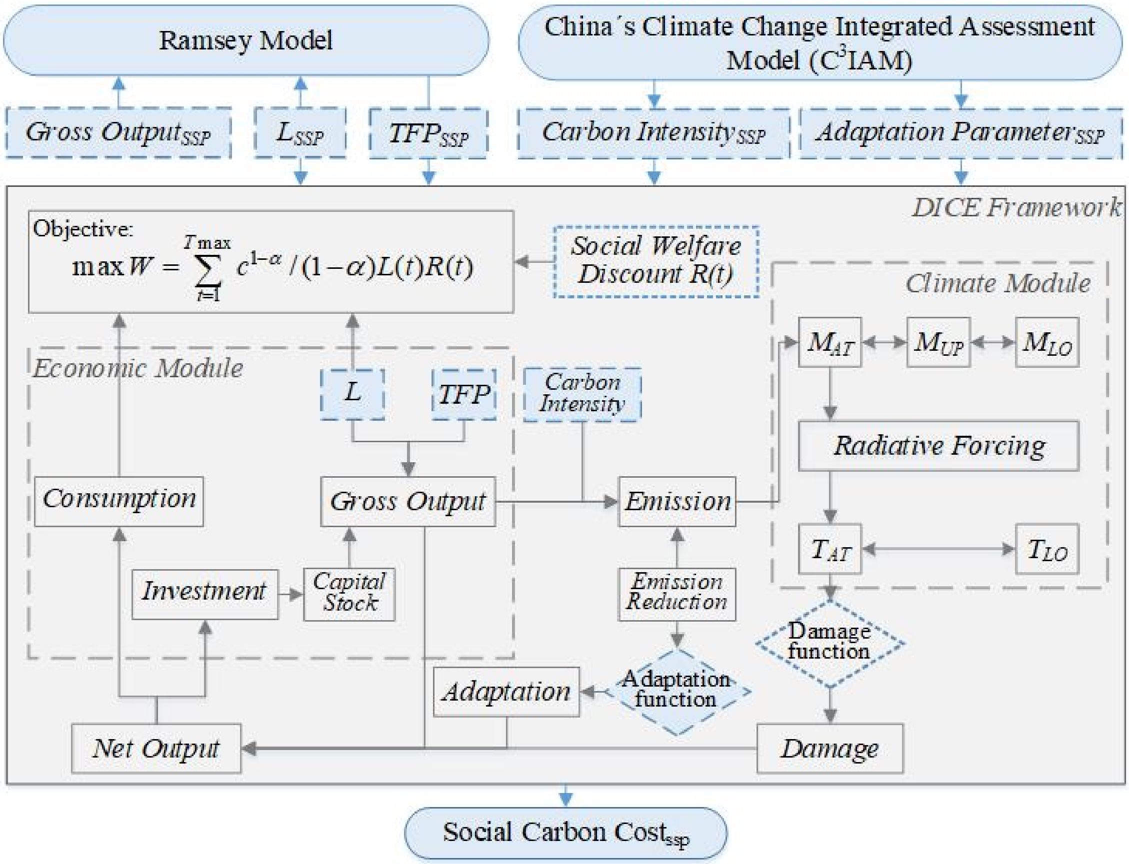

Figure 1. Research Framework. L: population, TFP: total factor productivity, c: consumption per capita, M_{AT}: atmospheric concentration of CO_2, M_{UP}: upper ocean/biosphere concentration of CO_2, M_{LO}: deep ocean concentration of CO_2, T_{AT}: atmospheric temperature, T_{LO}: lower ocean temperature

2.2 Characterizing the SSPs in the DICE model

2.2.1 Characteristics of the five SSPs

The SSPs consist of a set of quantitative projections and qualitative descriptions. The quantitative projections include population and economic growth. These factors are exogenous to most integrated assessment models that form the fundamental characteristics of each SSP. The qualitative narratives are thoroughly described in (O'Neill et al., 2017), including the aspects that are difficult to project quantitatively. To summarize, SSP1 represents the sustainable development path, SSP2 implies a development pathway consistent with typical historical patterns, and SSP3 is characterized by international fragmentation and regional rivalry. Low challenges to mitigation but high challenges to adaptation are observed in SSP4, which emphasizes extreme inequality. In contrast, SSP5 represents high challenges to mitigation and low challenges to adaptation, forecasting economic successes for both industrialized and emerging economies.

2.2.2 Qualify the SSPs in the DICE model

For the quantitative factors, the population can be directly set as exogenous in the DICE model. Using the gross output driven by the endogenous capital formation, we chose the total factor productivity (TFP) to reflect different growth rates under different SSPs. The factor is derived using the Ramsey model. The population and output projection methods of the SSPs are described in (Leimbach et al., 2017; Samir and Lutz, 2017).

For the qualitative factors, carbon intensity and the adaptation function are two other differentiating factors for SSPs. However, as they are highly related to the energy and sectoral assumptions, which cannot be directly reflected in DICE, C^3IAM provides the SSP baseline and combines the Representative Concentration Pathways (RCPs) with the SSPs (Wei et al., 2018). The baseline emission is aggregated from 27 sectors and can be input as the carbon intensity in DICE. The RCPs can be considered as a set of policy shocks to the CGE model, which results in a set of emission reduction percentages accompanied by their policy costs. We use the result to fit the adaptation function in DICE, and the regression results are listed in the Supporting Information.

2.3 Alternative damage functions and social welfare discount rate

The SCC is very sensitive to the damage function and social welfare discount rate. However, with our limited knowledge about the mechanisms of climate change, the accuracy of damage functions is unknown. The social welfare discount is valued not only as an economic term but also considered as an ethical primitive. Therefore, we provide the social carbon cost under nine damage functions and discuss the SCC under six alternative social welfare discount rates.

The damage function in DICE-2016R has been used to provide SCC estimations for the U.S. government. To consider the uncertainty of damage functions, we tested eight additional functions based on the meta-analysis by Richard Tol (Tol, 2018), which includes 27 published estimates of the economic impact of climate change. The piecewise linear function provides the best fit with the lowest standard error; however, Tol also used seven other forms to fit the data. Although some functions have a higher standard error of regression, we still include the results as possibilities. Together with the damage function in DICE-2016R, we estimate the SCC under 9 damage functions to consider all the possibilities (as shown in Table 1).

Table 1. Damage Function Based on Meta-analysis by Richard Tol (Tol, 2018)

Specification	Proposer	Standard Error of Regression
$0.236\,T^2$	DICE-2016R	
$(-0.74\,T)\,I_{T<1.01} + (1.41\,T\text{-}2.18)\,I_{T\geq 1.01}$	Meta-analysis	1.12
$0.12\,T + 0.16\,T^2$	Tol (2009)	1.17
$0.19\,T^2$	Nordhaus	1.25
$0.71\,T$	Hope	1.34
$0.02\exp(T) - 0.02$	Karp; Van der Ploeg	1.71
$4.2*10^{-175}\exp(\exp(T)) - 1.1*10^{-174}$	Golosov	2.10
$1.6*10^{-4}\,T^2\text{-}0.36\,T^2$	Weitzman	2.69
$2.6*10^{-5}\,T^2\text{-}0.35\,T^2$	Weitzman	2.73

Although the social welfare discount can be defined as an economic concept, many argue that the choice of discount is also an ethical primitive. Stern recommended a value of 0.1% (Stern, 2006). Nordhaus valued it in the Ramsey equation, resulting in an estimate of 1.5% (Nordhaus, 2017). The IWG provided evaluations using discounts of 2.5%, 3% and 5%. Thus far, however, the social welfare discount concept has not converged to a single value in the literature. The SCC is highly sensitive to the discount rate(Heal and Millner, 2014). To better illustrate the uncertainty caused by socioeconomic assumptions and damage functions, we chose the 1.5% economic discount rate for discussion. The alternative discounts, ranging from 0% to 5% SI, are discussed in Section 3.3.3, 3.3.3 Alternative Social Welfare Discounts.

3. *Results*

3.1 Evaluating the SSP outcomes in DICE

As shown in Figure 1, the socioeconomic assumption is accompanied by a particular emission trajectory. The emission patterns differentiate under each SSP, leading to increases in atmospheric concentrations, which indicate the long-term temperature trends. Temperature is the direct indicator of climate change and produces different degrees of climate damage, which further determine the SCC. Therefore, we chose emission, concentration and temperature to illustrate the major outcome of SSP in the DICE model (Figure 2). Compared with the five SSP marker scenarios(Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017), the DICE model considers the optimal emission reduction strategy under a cost-benefit analysis. The results are slightly lower than the baseline scenarios, but the relationships accord with the general narratives.

Under SSP5, industrial emissions are markedly higher than other scenarios because of industry's reliance on fossil fuels. Thus, SSP5 results in 130 $GtCO_2$ emissions in 2100. The emission trajectories of SSP1 to SSP4 diverge after 2050. SSP2 and SSP3 exhibit an increasing emissions trend until the end of this century; in 2100, their values are 65 $GtCO_2$ and 70 $GtCO_2$, respectively. With low challenges to mitigation, SSP1 and SSP4 both reach their emissions peaks in the middle of the century. Under SSP1, emissions reach 47 $GtCO_2$ in 2050 but decrease to 42 $GtCO_2$ by 2100. Under SSP4, the peak emission is higher at 48 $GtCO_2$ in 2055 and decreases more slowly to 45 $GtCO_2$ at the end of this century. Under SSP5, higher emissions will magnify the uncertainty of climate damage, resulting in a wider range of emissions trajectories. Under some damage functions, the optimal emission control rate results in an emissions decrease in SSP5, but under most scenarios, the emissions generally increase.

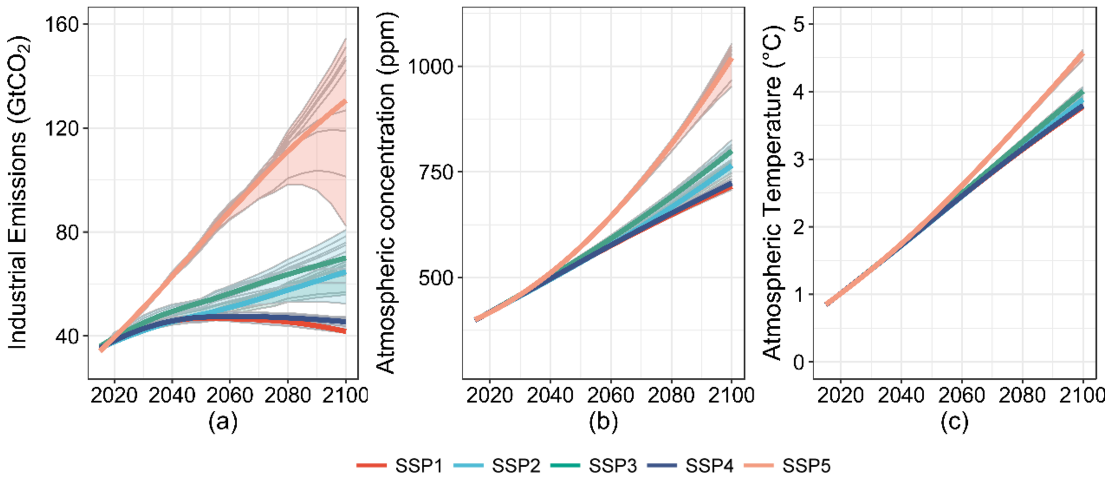

Figure 2. Industrial emissions and their influences on atmosphere concentration and temperature under the five SSPs: (a) industrial emissions. (b) atmospheric concentration. (c) atmospheric temperature. The gray lines indicate the results from nine different damage functions; the colored lines show the smoothed conditional means of the results under the five SSPs.

The difference in emissions is directly reflected by the atmospheric concentration trend, which determines the long-term growth of temperature. Under SSP 1 and SSP4, the concentration nearly stabilizes by the end of this century, reaching average levels of approximately 720 ppm. The concentrations in SSP2 and SSP3 continue increasing to 760 ppm and 799 ppm, respectively, by the end of this century. With high dependence on fossil fuels, in SSP5, the concentration rises to 1019 ppm by 2100. According to the IPCC Fifth Assessment Report (Pachauri et al., 2014), the concentration is likely (>66%) to cause temperature increases of up to 4°C by 2100 under SSP1–SSP4. At concentrations above 1000ppm, the SSP5 temperture is unlikely (<33%) to remain at 4°Cin 2100 and will continue to rise according to the concentration trend.

The result from the DICE model agrees with the IPCC result. Because the climate cycle is a long-term process, the temperature increases are quite similar among the scenarios. SSP5 has the largest temperature increase—4.6°C compared to the preindustrial level. In SSP1 to SSP4, temperatures increase by approximately 4°C, to 3.8°C, 3.9°C, 4.0°C and 3.9°C, respectively.

3.2 Estimate the Social Carbon Cost with Uncertainty

3.2.1 Impact of Socioeconomic Assumptions on Social Carbon Cost

Socioeconomic assumptions greatly affect the levels and trends of the SCC. Under the five SSP narratives, the SCC calculated under nine damage functions result in different uncertainty extents as shown in Figure 3.

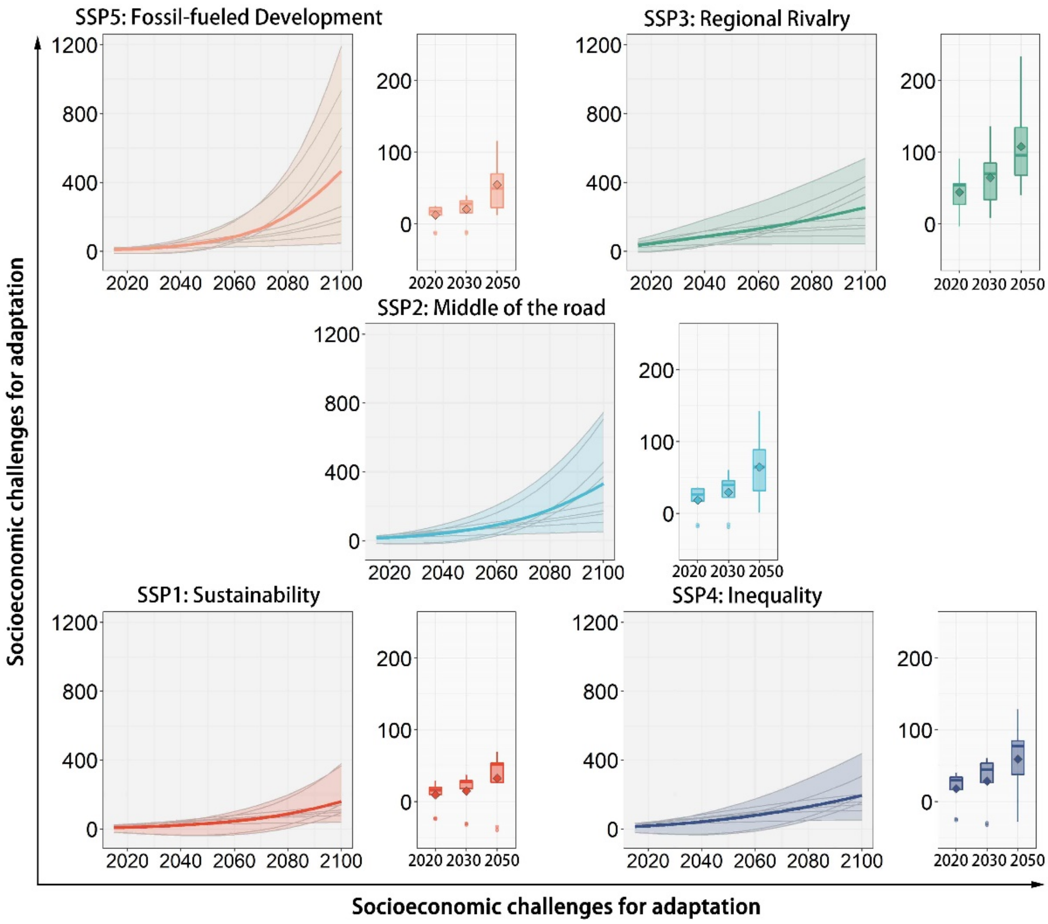

Figure 3. Social carbon cost ($/tCO2) under five SSPs. The gray lines show the SCC calculated under nine damage functions; the colored lines show the smoothed conditional means of the SCC.

In 2020, the average SCC estimations under SSP1, SSP2, SSP4 and SSP5 are 10$/t$CO_2$, 19$/tCO_2, 18$/t$CO_2$ and 12$/t$CO_2$, respectively. The SSP3, which represents high mitigation and adaptation challenges, has the highest SCC early in this century, reaching 45$/t$CO_2$ in 2020 and increasing to 108$/t$CO_2$ by 2050. This level is remarkably high compared with other scenarios, and it suggests that if the world socioeconomic conditions increasingly develop into regional rivalries, the SCC will undergo a significant increase. Under the benefit-cost framework, the SCC equals the carbon price under a tax or trade instrument (Nordhaus, 2013). In 2017, 19 carbon trading markets were in place with an average price of 9.1$/t$CO_2$, and 22 nations/sectors have implemented a carbon tax, which averages 29.9$/t$CO_2$ (World Bank, 2017). Under all the scenarios, the SCC is higher than the quota price but quite similar to the carbon tax. This result indicates that, thus far, the carbon trading system is not efficiently reflecting the social cost of emissions. However, as carbon taxes are implemented by governments, they can be targeted to maximize public welfare. Therefore, a carbon tax can better reflect the social costs of additional emissions.

Different socioeconomic assumptions can also alter the SCC trend, especially after 2050. SSP3 features a slow growth of SCC at high levels; its annual growth rate is 3% from 2015 to 2050 but the level is the highest among all scenarios. Social costs undergo rapid growth in SSP5, with an annual growth rate of 5% from 2015 to 2050 and continued increases thereafter at 4% annually until the end of this century. SSP1, SSP2 and SSP4 are characterized by medium growth throughout the century, with annual growth rates of 4% from 2015 to 2050. The SCC trend can be an important indicator of policy section among price and quantity instruments(Weitzman, 1974). Therefore, different socioeconomic developments may affect the choice of policy instruments.

Varying levels of uncertainty can be witnessed within the socioeconomic scenarios due to the impact of damage functions. Higher emissions magnify the uncertainty from climate damage, thereby resulting in a wider SCC range in SSP2, SSP3 and SSP5.

3.2.2 Impacts of Damage Functions on Social Carbon Costs

The SCC values under the nine damage functions can be divided into two groups, indicating different expectations for climate change. However, the choice of damage function will not reverse the SCC relationships under the five SSPs.

As shown in Figure 4, the SCC under the nine damage functions can be classified into ‘moderate’ estimation and ‘sharp change’ estimation. Moderate estimations include the five functions proposed by Hope, Tol and Nordhaus. Using these, the estimated SCC never exceeds 300$/t$CO_2$ in this century, and it reaches an average level of 157$/t$CO_2$ by 2100 under the five SSPs. In contrast, applying the damage functions provided by Weitzman, Karp and Golosov results in a sharp increase of SCC by the end of this century, reaching an extremely high average level of 864$/t$CO_2$ by 2100. The moderate estimation is mainly extrapolated from observation, while the sharp change group suggests that several of the climate system elements could be tipped into a different state by the temperature increase. According to the two damage functions from Weitzman, a modest increase of temperature will initially benefit the economics but then abruptly decrease after the tipping point. These functions result in an initially negative SCC, which indicates that the additional emissions will provide positive effects and a social welfare gain under a moderate temperature increase. Under SSP1 and SSP4, with low mitigation challenges, the negative SCC will continue until 2060 to 2075, while under SSP3, with high mitigation challenges, the SCC becomes positive between 2015 and 2020. Under the damage function from Golosov, the SCC increases from 13$/t$CO_2$ in 2015 to 1192$/t$CO_2$ in 2100, leading to enormous mitigation and adaptation pressures by the end of this century.

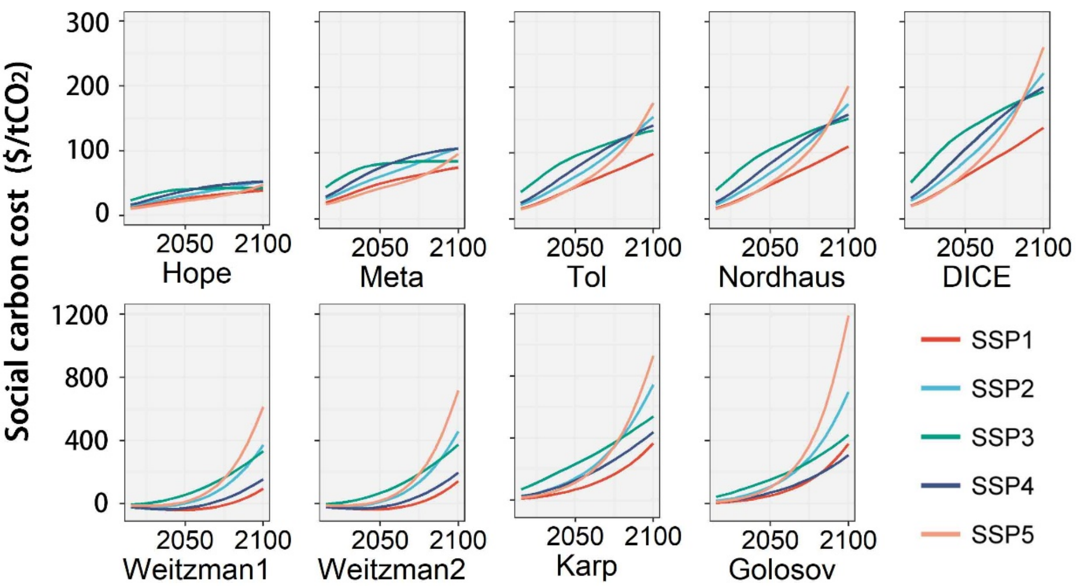

Figure 4. Social carbon cost ($/t$CO_2$) under nine damage functions.

Regardless of the damage function used, the SCC relationships under the five SSPs are not reversed. The sustainable development scenario (SSP1) always ranks the lowest under all damage functions. SSP5 is characterized as a rapid increase of SCC by the end of this century. SCC under SSP3 is initially high but has a low growth rate over the century. Moderate growth is also observed in SSP2, but the initial level is lower than in SSP3.

3.3.3 Alternative Social Welfare Discount

The social cost of carbon is also highly sensitive to the social welfare discount rate. Because climate damage mainly accrues over the long term, the discount rate affects how the prospect of future damage should be addressed today. A high discount rate will significantly reduce the present perception of future climate damage, which results in a low SCC. In contrast, when the climate damage has no future discount, so that people today are as concerned with their descendants' welfare as with their own well-being, ambitious climate actions should be taken immediately under high SCC. A near-zero discount rate highlights the ethical issues of climate policy, while the Ramsey discount emphasizes the economic benefits of adaptation. This section provides alternative SCC estimations under discounts of 0% to 5% and compares them with the carbon tax and quota price in 2017 to reflect the present policy intensity.

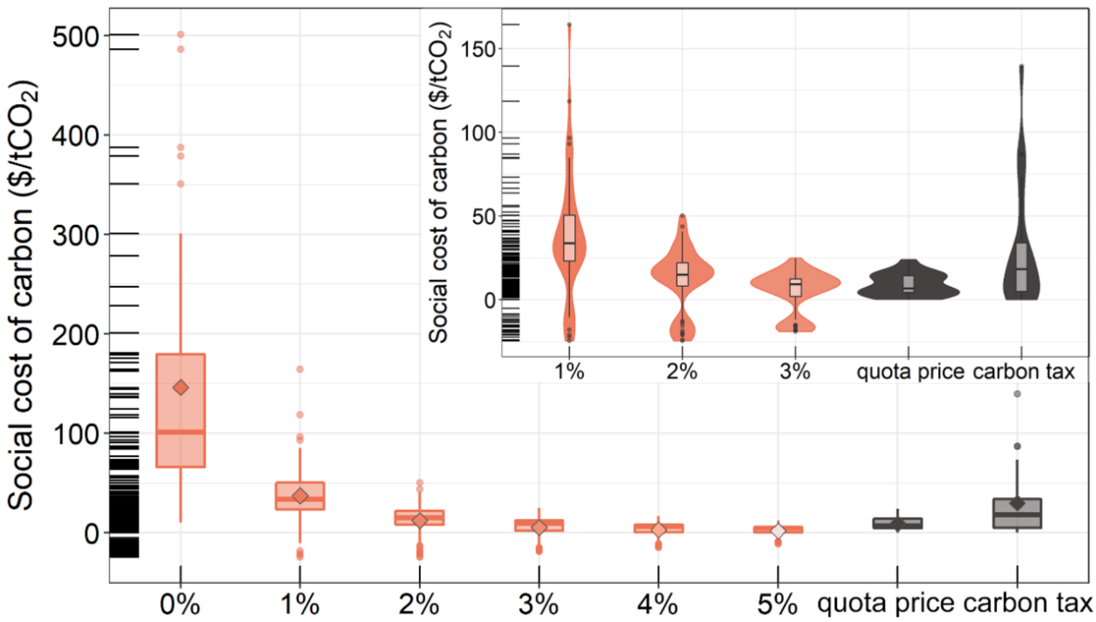

Figure 5. The social cost of carbon in 2020 under a 0%–5% social welfare discount compared with the carbon price in 2017.

Average SCC decrease exponentially from 0% to 5% (as shown in Figure 5). In 2020, the average SCC values under discounts from 0% to 5% SI are 146\$/tCO_2, 37\$/tCO_2, 12\$/tCO_2, 5\$/tCO_2, 3\$/tCO_2 and 2\$/tCO_2, respectively. A low discount rate substantially magnifies the uncertainty of impacts from emissions, temperature and climate, resulting in a wide range of SCC estimations—from -25\$/tCO_2 to 501\$/tCO_2 in 2020 under a 0% discount. When the discount rate exceeds 3%, the wellbeing of future generations has less influence on today's policy decisions, resulting in SCC values below 5\$/tCO_2.

The SCC provides a basis for pricing carbon; in 2017, the average quota price was 9.1$/t$CO_2$, while the carbon tax averaged 29.9$/t$CO_2$. Comparing these figures with our SCC estimates, the carbon tax indicates a discount rate preference of 1%, and the carbon quota price indicates a discount rate of 2% to 3%. However, although the average carbon tax can be as high as 139.58$/t$CO_2$ in Sweden, the mean distribution of the tax is still quite low.

4. Conclusions

As more countries begin to implement climate policy, estimating the SCC under a cost-benefit analysis is necessary to provide a pricing benchmark. The term has been used for carbon tax, tradable obligations or renewable portfolio standards(Burke, 2016). However, SCC estimation relies heavily on future assumptions (e.g., mitigation and adaptation challenges, population growth and economic development), a reliance that has not previously been recognized. Previous studies have discussed the population and economic impacts separately; however, these factors have a synergistic effect on all aspects. This paper is based on the five plausible future descriptions established by the climate change research community, and it provides the future social costs of emissions under different development pathways.

We found that the scenario representing extreme regional rivalry (SSP3) will cause substantial increases in the SCC in the near term, indicating that if more trade tariffs are implemented due to increasing regional conflicts, the social carbon cost today will be underestimated. Under SSP5, where developing countries emerge by exploiting abundant fossil fuels, the pressures for mitigation will become unbearable by the end of this century. The SCC is initially at a relatively low level. Then, it undergoes a rapid increase after 2060 and reaches an average level of 471$/t$CO_2$ by 2100. The damage this growing trend will cause is unstoppable, according to the atmospheric concentration; thus, it demands an increase in attention to the clean development of emerging economies. SCC under increasing inequality (SSP4) is similar to the sustainable development pathway (SSP1) and maintains a low growth rate at a moderate level. The scenario that follows the historical development patterns (SSP2) experiences the same annual growth rate as SSP1 but at a higher social cost and with more uncertainty. The results of this study highlight the importance of avoiding regional rivalries and expending efforts to ensure the green development of emerging economies. Our results also provide a breakeven carbon price for policy makers who hold different attitudes concerning the future and they facilitate mitigation and adaptation analysis under the SSPs. Because the SCC is still under discussion and difficult to explain even at the domestic level (Fraas et al., 2016; Guivarch et al., 2016), we defer a discussion of regional SCC for the future.

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